Current deformation rates and extrusion of the northwestern Okhotsk plate, northeast Russia

D. Hindle, K. Fujita, and K. Mackey

Department of Geological Sciences, Michigan State University, East Lansing, Michigan, USA

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[1] Northeast Asia is a region of broad deformation resulting from the convergence of the Eurasian (EU) and North American (NA) plates. Part of this convergence has been suggested to be relieved by the extrusion and deformation of the Okhotsk plate (OK). Three models for the deformation of the seismically active northwestern corner of the Okhotsk plate, based on different modes of deformation partitioning, are calculated and compared to observations from GPS, seismicity, and geology. The results suggest that this region is being extruded southeastward and deforming internally by a mixture of pure contraction, "smooth" extrusion, and "rigid" extrusion. Calculated extrusion rates are $\sim$3–5.5 mm/yr, comparable to estimates from geologic data, and internal deformation rates are $\sim 3.0 \times 10^{-9}$ yr $^{-1}$. Internal deformation may be only partially accommodated by seismicity, but the short time span of seismic data leaves this subject to large uncertainty. **Citation:** Hindle, D., K. Fujita, and K. Mackey (2006), Current deformation rates and extrusion of the northwestern Okhotsk plate, northeast Russia, *Geophys. Res. Lett.*, *33*, L02306, doi:10.1029/2005GL024814.

1. Introduction

[2] Nearly 40 years after the establishment of the theory of plate tectonics, the plate geometry in northeast Asia remains enigmatic. This is partially a consequence of the broadening of the zone of deformation between North America (NA) and Eurasia (EU) as defined by seismicity. The zone is sharply defined along the Mid-Atlantic and Arctic Mid-Ocean (Gakkel) ridges [*Eldholm et al.*, 1990], but becomes diffuse throughout continental northeast Asia (Figure 1) [*Parfenov et al.*, 1988]. Hence, much debate still surrounds the existence and nature of plate boundaries across eastern Siberia, notably in the Sea of Okhotsk region, where a separate Okhotsk plate (OK) has been discussed for many years [e.g., *Chapman and Solomon*, 1976; *Savostin et al.*, 1983; *Cook et al.*, 1986; *Seno et al.*, 1996]. Attempts to resolve a separate plate have met with some success [*Riegel et al.*, 1993; *Seno et al.*, 1996], but the possibility cannot be excluded that a zone of distributed deformation and/or micro-plates or blocks would better explain some of the seismicity and focal mechanisms in the region.

[3] In this paper we model a range of deformation scenarios for the northwestern corner of OK using differing assumptions about the partitioning of deformation. We refer to this region, following common usage, as part of OK. It was chosen because of a good seismic network (focal mechanism data for the last $\sim$40 years [*Imaev et al.*, 2000]), some GPS data [*Steblov et al.*, 2003], and good field data (geological observations mostly on the presumed OK-NA boundary [*Imaev et al.*, 2000; *Smirnov*, 2000]). It has a high level of distributed seismic activity [*Parfenov et al.*, 1988] and is a region of high deformation which we model by assuming purely contractional (no extrusion), distributed (smoothed extrusion) or rigid (maximum extrusion) behavior. This yields estimates of both the internal deformation and boundary slip rates of this part of OK which can be compared to the geologic and geophysical observations.

[4] The geometry of OK, as defined below, exerts strong controls on the mode and rate of its deformation. Its northwestern end tapers to a point at the presumed EU-NA-OK triple junction, while the EU-NA pole of rotation lies only slightly north of this triple junction and very close to the EU-NA plate boundary itself [*Cook et al.*, 1986; *Sella et al.*, 2002]. While the proximity of the pole means linear velocities are relatively low, this plate configuration implies that OK is being squeezed between the converging EU and NA plates. Hence, the crust forming the northwestern extremity of OK (essentially the continental region north and west of Magadan) has to either deform internally or extrude southward along the OK-NA and OK-EU plate boundaries. Any extrusion of northwestern OK would also require strike-slip faulting on one or both of these boundaries. Because of the lack of quantifiable data, we do not address the question of whether OK has a rigid core or how the deformation is accommodated south and east of the coastline.

2. Modeled Deformation of the Northwestern Okhotsk Plate

[5] We model three deformation scenarios for the northwestern corner of OK. All use the EU-NA rotation pole and uncertainties of *Sella et al.* [2002] to derive velocity fields for the models (see auxiliary material[1]). The plate boundary was parameterized as a polygon using the OK-NA and OK-EU boundaries suggested by *Fujita et al.* [1997]. In their model and following extensive Russian work [e.g., *Parfenov et al.*, 1988; *Imaev et al.*, 2000] the OK-NA boundary is traced along the Ulakhan fault, a distinct lineament visible in satellite imagery and accompanied by teleseismic earthquakes. The fault shows offsets in post-Pliocene river drainage and Recent alluvial fans. The OK-EU boundary, which is less well constrained, is located along the Ketanda

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024814.

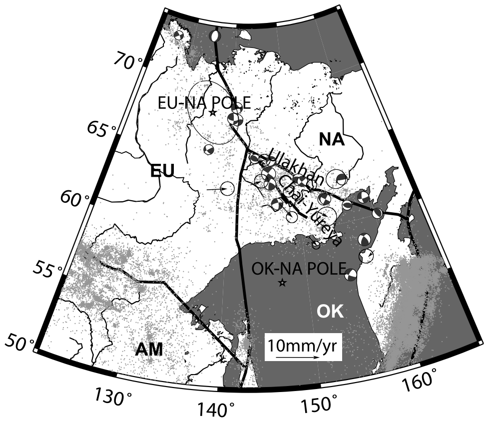

Figure 1. The diffuse seismicity of Northeast Asia. Minor epicentres shown as grey dots, major earthquake (>M_s5) along the OK-NA and EU-NA boundaries shown as focal mechanisms. GPS vectors and 1σ confidence ellipses from *Steblov et al.* [2003] are also displayed.

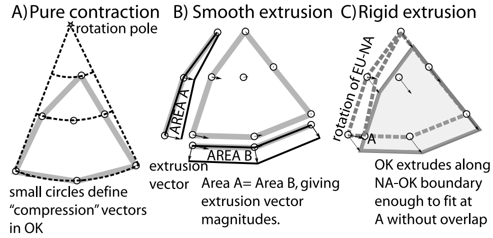

Figure 2. Sketches of boundary conditions for the 3 deformation models. (a) Pure contraction, velocities in OK follow tangents to small circles around the EU-NA pole, but diminish to zero linearly within OK. (b) Smooth extrusion where contraction vectors have an additional extrusion component whose magnitude compensates instantaneous area loss on the EU-OK boundary. (c) Rigid extrusion, where OK extrudes as a single block of material parallel to the NA-OK boundary, until the southern end fits within the new position of the EU-OK boundary.

fault of *Imaev et al.* [2000], which is also noted in satellite imagery and has lesser seismicity associated with it. The northern end of the boundary is somewhat arbitrary as no clear lineaments exist near the triple junction. For each model, we invert the resultant velocity field to derive an approximate strain rate tensor over OK by splitting the region into triangles with the velocity points as vertices and then calculating the strain rates for individual triangles before weighting, summing and averaging them to give a single strain rate tensor for OK (Table 1). Due to the offset of the EU-NA pole from the OK apex, migration of the EU-OK-NA triple junction is expected. The velocity point at the apex of OK is assigned a triple junction migration velocity (1.0 mm/yr) from the assumed overthrusting of the EU-OK boundary over the OK-NA boundary calculated from the velocity of EU at the EU-OK-NA triple junction.

[6] In the first model, we assume "pure contraction" where EU rotates with respect to a fixed NA. The resulting deformation is accommodated evenly across OK so that velocities reduce linearly within OK along small circles centered on the EU-NA pole from the EU-OK boundary (Figure 2a). Velocities of points on the EU-OK boundary, and within OK, are calculated from $\omega \times \mathbf{r}$, where ω is the angular velocity vector of the rotation pole and $\mathbf{r}$ the position vector of the point at which the velocity is calculated. The two points on the OK-NA boundary are considered stationary. In this case, the finite geometry of OK leads not only to contraction along small circle tracks but also a small amount of shear strain caused by a north-south velocity gradient due to the irregular shaped EU-OK boundary and the offset of the EU-NA pole from the OK apex. Hence, the final strain rate of the region reflects both shear and contractional strain components. For this model, the shortening axis has the greatest magnitude (-3.9×10^{-9} yr $^{-1}$), implying tectonic thickening of OK. The average shortening direction is very close to the trends of the velocity vectors (~061°), showing that contractional strain dominates (Figure 3a).

Table 1. Strain Rates Calculated for Okhotsk Plate Apex Region, Giving Contraction, Extension Magnitudes, Degrees Clockwise From North of Contraction Axis and a Vertical Thickening Parameter Calculated to Conserve Volume[a]

Data	Contraction, yr^{-1}	Extension, yr^{-1}	Cont. Azi., ° From N.	Vert. Thick., yr^{-1}
		Model		
contr.	−3.9 ± 0.5 e-9	3.7 ± 0.5 e-9	61 ± 1.5	2.3 ± 1.3 e-10
smo. ext.	−3.8 ± 0.8 e-9	4.6 ± 0.5 e-9	72 ± 1	-
rig. ext.	-	-	-	-
		Obs.		
GPS	−6.6 e-10	4.8 e-9	57	−4.1 e-9
Eq.	−3.8 e-10	3.5 e-10	81	2.6 e-11

[a]Confidence limits for approximate 1σ variations of EU-NA pole and angular velocity.

[7] The second model represents "smooth" extrusion of OK (Figures 2b and 3b). We assume that surface area lost due to inward motion of the EU-OK boundary (pure contraction) is compensated by area gain at the southern end of the region, defined by velocity components directed orthogonal to the local direction of pure contraction. The resulting extrusion vectors are of equal magnitude (~3.0 mm/yr) on the three southern nodes, and are added to the "contraction" velocity used in the preceding model. The second ring of nodes lying to the north have extrusion magnitudes half those of the southern end. Finally, the apex receives the same triple junction migration velocity as before (see auxiliary material). The extrusion leads to differential strike slip motion along the OK-NA boundary, with slowest rates at the apex constrained by triple junction migration (~1.0 mm/yr) and fastest on the southern termination in the model (~3.0 mm/yr) where the full magnitude of extrusion is obtained (Table 2). Strain rate magnitudes are close to those for pure contraction, while the shortening direction (~072°) is rotated slightly southward (Table 1).

[8] The third model is of "rigid" extrusion where the modeled portion of OK is assumed to behave as a rigid block and extrude along the NA-OK boundary (Figures 2c and 3c), until it fits within the new width of the southern end of the model after EU has rotated. This model assumes a gap opens between the extruded OK block and EU and also along the northern portion of OK-NA since the block extrudes faster than triple junction migration can occur. As OK is rigid, internal velocities are constant (see Table S1) and there is no internal strain. This model also yields a theoretical

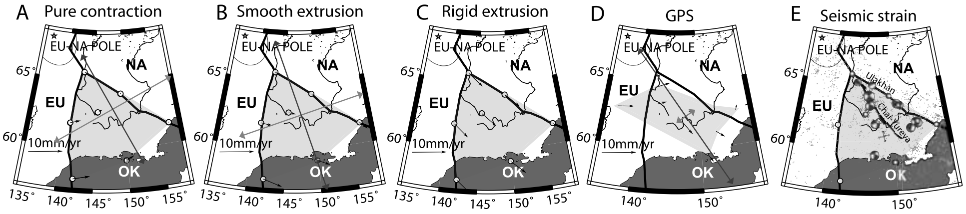

Figure 3. Model and observed strains and velocities in OK. (a) Pure contraction model of OK. Velocity vectors are shown across the polygon where strain rate is calculated. Principal strain rate axes are thicker grey arrows. (b) Smooth extrusion model. (c) Rigid extrusion model. (d) GPS strain rate from GPS vectors bounding and within box shaped region shown (see auxiliary material). (e) Seismic deformation rate, based on focal mechanisms (see auxiliary material). Strain rate data listed in Table 1.

maximum rate for strike-slip offset occurring along OK-NA of ~5.5 mm/yr.

3. Observed Deformation of the Northwestern Okhotsk Plate

[9] Figure 3d summarizes the GPS data of *Steblov et al.* [2003] from sites within OK and on adjacent EU and NA (see auxiliary material). The shaded region bounded by the sites has been chosen to most closely correspond to the shaded area of Figure 3a and 3b, but does include portions of EU and NA assumed rigid in our models. The GPS velocities from the shaded region were inverted for strain rate, and yield a strongly extensional average strain over the region (4.8×10^{-9} yr^{-1}), with axes orientations comparable to the models (short axis ~054°). The velocity vectors show two trends, with points near the OK apex apparently moving along small circle tracks about EU-NA whilst more southerly vectors suggest some form of extrusion. 2D backslip modeling suggests a ~1–2.5 mm/yr northwest directed motion in the study area due to interseismic, elastic strain accumulation from the Kamchatka subduction zone, which may transiently reduce the motions of the southern GPS stations [*Bürgmann et al.*, 2005].

[10] Figure 3e shows the result of a seismic moment tensor sum for the earthquakes shown within the shaded area (see Table S3). Although the region is one of diffuse seismicity (Figure 1), only the larger (M > 5) events contribute significantly to the deformation and have determined focal mechanisms. Using the method described by *Klosko et al.* [2002], we calculate deformation rate over an equivalent volume to that of the shaded area, assuming a maximum depth of seismic deformation of 20 km, and a time span of 30 yr. Resultant strain axes are dominated by compression (-3.0×10^{-10} yr $^{-1}$) with shortening again directed close to the modeled pure contraction vectors (~081°). The seismic moment release, and hence seismic strain rate is dominated by one large earthquake, the May 18, 1971, M_w 6.4, strike-slip event [*Fujita et al.*, 2002], which occurred on the Chai-Yureya fault, located within, and causing internal deformation of, OK. Because this one event dominates the moment release, comparison of the seismic strain rate to the modeled rate is difficult; adding a second event with the same focal mechanism and moment would increase seismic strain rates to $\sim 1 \times 10^{-9}$ yr^{-1}. The direction of shortening, however, is essentially the same whether one includes, or excludes, the 1971 event.

[11] Although several other moderate earthquakes occur on or near the Chai-Yureya lineament (primarily near the 1971 event), a significant number are located on or near the Ulakhan fault, which can be traced over a much longer distance [*Imaev et al.*, 2000], marks the general edge of the region of high seismicity, offsets the Mio-Pliocene drainage network [*McLean et al.*, 2000], and apparently is active today (offset Quaternary alluvial fans (V. Egorov, personal communication, 2004]). Offset indicators suggest left-lateral motion, and this fault is considered the likely candidate for the NA-OK plate boundary.

4. Tectonic and Geologic Implications

[12] The major problem in delineating OK remains the fact that its northwestern corner is deforming internally, relatively quickly. Our models confirm the geometric necessity of this, and suggest rates similar to those obtained for other plate boundary zones [*Gordon and Stein*, 1992; *Kreemer et al.*, 2003]. Earthquake and GPS data also suggest considerable internal strain near the apex of OK. Hence, the northwestern part of the OK plate as it is usually defined is not expected to fit well into a plate tectonic paradigm defined by assumptions of purely rigid plates. This does not, however, rule out plate-like behavior by other (core of the Sea of Okhotsk) parts of OK.

[13] The models describe end member scenarios for accommodating boundary displacements imposed by the adjacent EU and NA plates. The pure contraction model predicts shortening close to the trends of EU-NA motion but allows for virtually no slip on the OK-NA boundary (Ulakhan fault). This contrasts with both the earthquake focal mechanisms (mostly strike-slip) and GPS data from the southern set of stations (extruding), although near the OK apex, the "pure contraction" velocity field fits quite well. Shortening strains at $\sim -3.9 \times 10^{-9}$ yr^{-1} and directed ~061° could be accommodated on a series of overthrusts orthogonal to displacement in a deformation similar to that proposed by *Bobronikov and Izmailov* [1989].

Table 2. Ulakhan Slip Rates and Triple Junction Migration Rates for the Deformation Models[a]

	Ulakhan, mm/yr			TJ, mm/yr		
Data	Min	Prob	Max	Min	Prob	Max
Contr.	-	-	-	0.5	1.0	1.6
Smo. ext.	1.9	3.0	3.6	0.5	1.0	1.6
Rig. ext.	4.7	5.5	6.4	0.5	1.0	1.6

[a]Mimimum/maximum values calculated from 1σ confidence intervals of EU-NA pole of rotation and angular velocity [*Sella et al.*, 2002].

[14] The smooth extrusion model, on the other hand, allows differential strike-slip motion on the OK-NA boundary, increasing from the apex southward (Table 2). This suggests offset indicators should show increasing left-lateral offset southward on the Ulakhan fault. Moreover, the OK side of the Ulakhan would be stretched. However, as surface area is being conserved, deformation could theoretically be accommodated by purely strike-slip faulting, which is compatible with the few focal mechanisms for internal deformation of OK, although predicted strain rates again exceed observed seismic ones.

[15] The rigid extrusion model gives highest possible slip rates on the Ulakhan fault (~5.5 mm/yr). These slip rates are constant along the length of the fault and result in extension rates equal to slip rates along the EU-OK boundary and at the OK apex. The interior of OK undergoes no internal deformation. Nevertheless, the slip rate along the Ulakhan fault is very close to that predicted by the OK-NA pole of *Sella et al.* [2002]. This rate is also consistent with previous estimates of the slip on the Ulakhan fault of ~5 mm/yr [*Imaev et al.*, 2000; *McLean et al.*, 2000]. Moreover, the constant slip rate along the Ulakhan fault matches the constant offset of drainage networks along a long segment of the fault [*McLean et al.*, 2000] better than the variable amounts predicted from smooth extrusion. GPS velocities in the south also fit quite well to such a model. However, the clear evidence for internal deformation from seismicity and satellite observed lineaments [*Smirnov*, 2000], and to some extent from GPS, rule out a model which localizes all deformation on the boundaries of this part of OK.

5. Conclusions

[16] Considering the advantages and pitfalls of the different models, it is clear that no single mode of deformation fits definitively better than the others. Rigid extrusion may closely match likely slip rates on the Ulakhan fault, suggesting that the boundary zone of OK is a relatively integral piece of crust adjacent to a zone of localized slip on the plate boundary. However, a glance at Figure 1 and consideration of the distribution of focal mechanisms shows that a substantial portion of the apex zone of OK is deforming internally by diffuse micro-seismicity (distributed/smooth), but some sharp boundaries allowing block like behavior also exist (e.g., the Chai-Yureya and other lineaments).

[17] Hence, it appears that the EU-OK-NA system displays a particular style of deformation between contraction, smooth extrusion, and rigid extrusion and this is probably a function of the peculiar plate geometry of a near juxtaposed triple junction and pole of rotation.

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D. Hindle, K. Fujita, and K. Mackey, Department of Geological Sciences, Michigan State University, 206 Natural Sciences Building, East Lansing, MI 48824, USA. (hindle@msu.edu)